The Pierre Auger Observatory

D. Zavrtanik[a] for the P. AUGER COLLABORATION *

[a]Nova Gorica Polytechnic,
P.O. Box 301, 5000 Nova Gorica, Slovenia

We present the scientific motivation, conceptual design and status of the P. Auger Observatory, a hybrid detector designed to measure both the longitudinal and the lateral profile of giant air-showers produced by cosmic-rays of energy above 10^{19} eV. Two ground arrays of water Čerenkov tanks overlooked by fluorescence detectors will cover an area of 3000 km^2 each. They will be build in the Southern and Northern hemisphere to provide full sky coverage. The total aperture of 14000 km^2sr will allow to study all observable aspects of cosmic rays from below 10 EeV up to arbitrarily high energies with an unprecedented accuracy.

1. INTRODUCTION

Cosmic rays were discovered at the beginning of this century by V. Hess. Since that time experiments have shown that they are predominantly atomic nuclei ranging in energy from less than 10^6 eV to more than 10^{20} eV. The fluxes of cosmic rays span over a wide range from more than 1 $cm^{-2}s^{-1}$ at 100 MeV to approximately 1 $km^{-2}century^{-1}$ above 100 EeV.

In 1938 P. Auger demonstrated that cosmic-ray spectrum extends beyond 10^{15} eV [1]. Today there is a plausible understanding that cosmic rays up to 10^{15} eV are produced by shock waves of supernova explosions and the sources lie in our galaxy. Following the Auger's work the energy spectrum of the cosmic rays was measured to higher energies by Rossi, Clark and co-workers [2]. The experimental efforts culminated in the large cosmic rays detector built by J. Linsley and collaborators at Volcano Ranch in New Mexico, USA. This detector was an array of scintillation counters spread over an area of 10 km^2. The cosmic rays were detected by the air showers produced by the primary particle in the atmosphere. In 1963 they reported a shower produced by a cosmic ray of energy 10^{20} eV [3].

In the last decade, a dozen of cosmic ray events have been reported well in excess of 10^{20} eV [4], [5] followed by recent experimental observation of 6 extremely high-energy events by AGASA [6]. Since there have been no published criticism of the determination of the energy of these events it is almost impossible that the detected events could result from experimental biases or calibration errors. The fact that there is no easy explanation of these events calls for new high statistics experiments.

At present the largest operating detector is AGASA array in Japan [5] with an acceptance of 125 km^2sr for cosmic rays above 10^{19} eV. In addition, the High Resolution Fly's Eye experiment in Utah is close to completion and ready to take data in stereo mode. Its time averaged acceptance is 1000 km^2sr above 10^{20} eV.

*Argentina: CONAE-IAFE Buenos Aires, CRICyT Mendoza, Universidad Nacional de La Plata, IAR Villa Elisa, TANDAR-CNEA Buenos Aires, Centro Atómico Bariloche; **Armenia:** Yerevan Physics Institute; **Australia:** University of Adelaide; **Bolivia:** University of La Paz; **Brazil:** University of Campinas, University of Sao Paulo, CBPF-Lafex Rio de Janeiro, Federal University Rio de Janeiro; **China:** IHEP Beijing; **France:** ENST Paris, LTF Observatoire de Besancon, Collège de France, LPNHE Université Paris 6; **Germany:** FZK-HPE and FZK-IK Karlshruhe, Universitat Karlsruhe; **Greece:** NTU Athens; **Italy:** INFN Catania, University of Milano, University of Roma 2, University of Torino; **Japan:** ICRR Tokyo; **Mexico:** BUAP Puebla, CINVESTAV-IPN, UNAM, UMSNH Morelia; **Poland:** INP Jagiellonian University Krakow, University of Lodz; **Russia:** MEPhI Moscow; **Slovenia:** Nova Gorica Polytechnic; **UK:** University of Leeds; **USA:** University of Colorado Boulder, EFI University of Chicago, FNAL, Louisiana State University, Michigan Technological University, University of New Mexico, Northeastern University, Pennsylvania State University, University of Utah; **Vietnam:** DNRI-VAEC Dalat, HINCST-VAEC, Hanoi.

The P. Auger Collaboration has started the construction of Southern Observatory near Malargue in Mendoza province, Argentina. Its final aim is to build two observatories (one in the northern and one in the southern hemisphere) for a high statistics measurement of extremely high-energy cosmic-rays with an overall acceptance of 14000 $km^2 sr$ in order to resolve the cosmic-ray puzzle in the energy region above 10^{20} eV.

2. SCIENTIFIC MOTIVATION

The energy spectrum of cosmic rays expands over 13 orders of magnitude in energy and 34 orders of magnitude in flux (Fig. 1) and exhibits a simple power law almost over the whole energy range. However, at energies above $10^{18.5}$ eV an unexpected structure in the spectrum can be observed (see Fig. 2) despite the fact that statistics is rather poor due to extremely low fluxes. Matching the observations to production and propagation models has proven to be very difficult. In the known astrophysical context, it is a challenge to explain the acceleration of particles to the energies above 10^{20} eV. The suggested models for acceleration fall into the following classes: diffusive shock acceleration (first order Fermi acceleration), acceleration in strong fields associated with accretion disks and compact rotating objects and acceleration in catastrophic events.

Perhaps, the favoured mechanism is the Fermi acceleration operating in extended sources [9]. For a variety of acceleration mechanisms, including Fermi acceleration, the maximum possible energy obtained by a particle of charge Ze is:

$$E_{max} \approx \beta \times Ze \times B \times L \qquad (1)$$

where β is a characteristic relative velocity within the system, and B and L field strength and the size of the accelerating region, respectively (see [10]). Fig. 3 shows B and L for a number of candidate astrophysical sources of high-energy cosmic rays. If one looks for the sites where a proton can reach the energy of 100 EeV, one can see that very few possibilities remain above the corresponding diagonal line on Fig. 3. These are: radio galaxies in the large L - low B region, neutron stars in low L - large B region and active galactic nuclei (AGN) in between. Although the acceleration mechanism is different, these are the most powerful candidate accelerators in our Universe. However, there is no general agreement in the community that any one of these accelerators is able to reach energies in the ZeV region. The most extreme predictions usually limit the accelerating power of such systems to a maximum of 10 to 100 EeV. However, some authors do not exclude the possibility that diffusive shock acceleration in quasars and radio galaxies may give a proton an energy around 1 ZeV [11].

The maximum possible energy of a particle exiting the source may be lower than suggested above due to energy loss processes. For example, synchrotron radiation is important for protons of

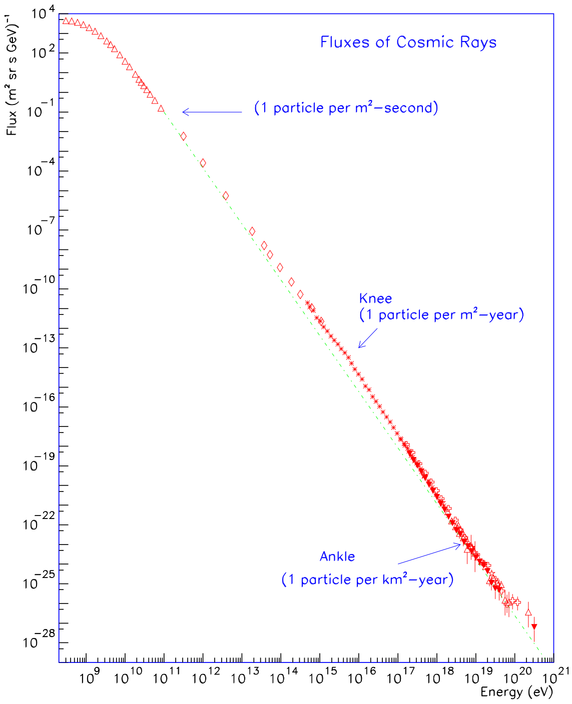

Figure 1. Differential energy spectrum of the cosmic rays with some indications of integrated fluxes per steradian [7].

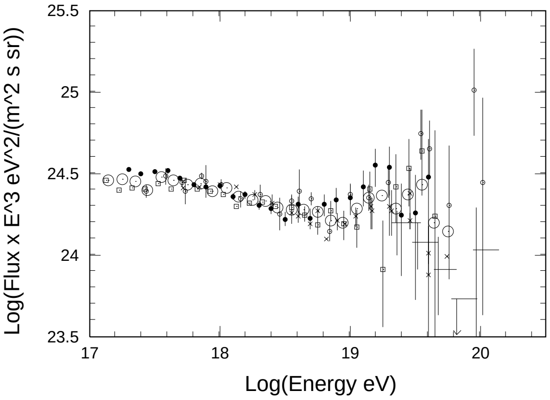

Figure 2. Detailed cosmic ray flux multiplied by E^3 at extremely high energies [8]. Recent AGASA results [6] are not shown.

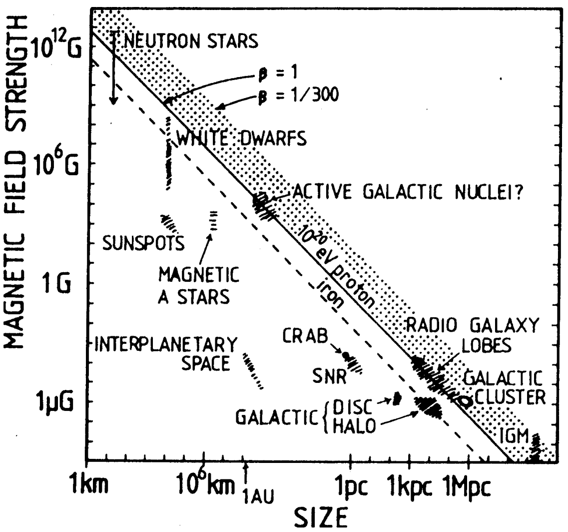

Figure 3. Various candidate astrophysical particle accelerators presented as a function of their magnetic fields and spatial extensions [10].

extremely high energies in the regions where the magnetic field strength is high. Losses due to photo-pion production are important in compact regions with intense radiation fields.

Soon after the discovery of the cosmic microwave background (CMB), it was pointed out by Greisen [12], Zatsepin and Kuz'min [13] that CMB may render the Universe opaque to cosmic rays of sufficiently high-energies. The threshold for pion photo-production (via Δ resonance) through the reaction of protons or neutrons on CMB photons occurs at the energy of approximately $10^{19.7}$ eV. Successive interactions reduce the energy of a nucleon until it falls below threshold. This effect is known as a GZK cut-off. Characteristic attenuation lengths for the protons at the highest energies are of the order of 10 Mpc which is a small distance on the cosmological scale. Energetic nuclei and photons also loose energy by photo-disintegration and pair production, respectively. Only neutrinos or unknown neutral weakly interacting particles would be immune but their interaction probability with atoms in the atmosphere would also be negligible unless the cross-section becomes strong [14]. Thus, there exist limits to the distance to the sources of the most energetic particles. For any observed cosmic ray energy, the distance limit is nearly independent of the initial particle energy, if it is above the GZK cut-off. Fig. 4 shows the probability that a cosmic ray detected at energy E would have travelled a distance D (in Mpc). In particular, for particles detected with the energy equal to 300 EeV, only 4 % of them should have travelled farther than 30 Mpc, and fewer than 0.4 % of them farther than 50 Mpc. GZK cut-off should be manifested in the observed spectrum as a strong suppression near $10^{19.7}$ eV, with a possible pile-up in the differential spectrum just below that energy threshold. The detailed shape of the spectrum will depend on the source distribution in space and time as well as the initial production spectra. On the other hand, the evidence of beyond GZK cosmic rays raises questions on how the cut-off could be violated.

A way to account for super-GZK cosmic rays without invoking dominance by nearby sources is to suppose that particles are produced with an extremely hard source spectrum. Such scenarios have not so far been proposed in the con-

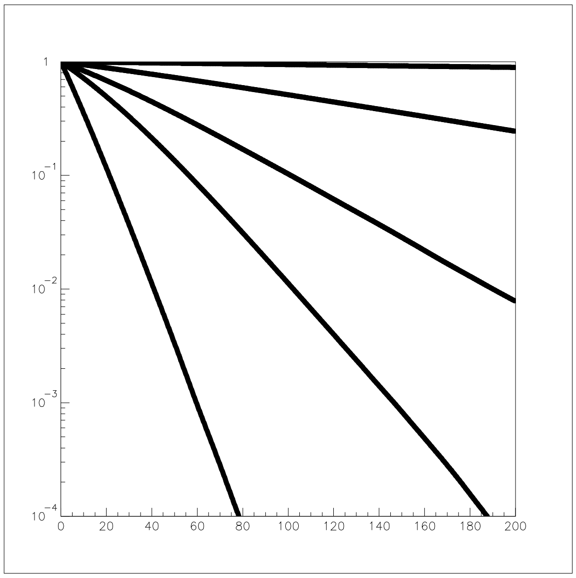

Figure 4. Probability (y axis) that a detected particle has travelled farther than a distance D in Mpc (x axis).The curves in descending order pertain to primary energies of E = 40, 60, 80, 100, 300 EeV.

text of bottom-up acceleration mechanisms. But, they do occur in top-down acceleration processes like topological defect annihilations [11]. In that picture, the spectrum results from the decay of super-massive X particles that are radiated by the topological effects formed in the early universe as a product of spontaneous symmetry breaking implicit in some Grand Unified Theories [15].

3. AUGER OBSERVATORY

The Auger Observatory is designed to make a definitive study of the mysterious cosmic ray events in the energy region above 10^{20} eV. The most important requirement of a dedicated experiment is to accumulate statistics. The detector must be able to measure the energy of the incoming cosmic rays with a resolution of approximately 10 %. It must also have a good resolution on measuring the direction of the cosmic ray since we would like to open the window to cosmic ray astronomy. And finally, the identity of the incident particles must be determined at least on the statistical, if not individual, basis.

The P. Auger Observatory offers also a window for neutrino astronomy above 10^{17} eV, with the observation of very inclined showers induced deeply in the atmosphere. The crucial criterion to distinguish them from the background is the characterisation of the EM component at ground level through the time spread of the signal. With some reasonable assumptions of the selection criteria, the expected acceptance is about 15 to 20 km^3 of water equivalent at 10^{19} eV and is slightly increasing above. Details of the P. Auger Observatory capabilities for measuring high-energy neutrinos can be found elsewhere [16].

3.1. Method

An incoming cosmic ray interacts in the upper atmosphere producing a cascade which can build up to some 10^{11} particles when the primary particle has an energy of 10^{20} eV. At each generation about 1/3 of the available energy is transferred to an electromagnetic cascade through the prompt decay of neutral pions. The hadronic cascade proceeds until the charged pion energy is degraded to the point ($\approx$ 20 GeV) that decay to muons become more probable than further interactions. This means that the predominant particles in the shower are electrons, photons and muons. At approximately 1500 m above the sea level more than 50 % of the shower particles are within the Molière radius of 80 m from the shower core. Far from the core ($\geq$ 500 m) the energies of the EM particles are around 10 MeV while the muons carry approximately 1 GeV of energy. At large distances from the shower axis the particles arrival is spread out in time by more than 1 μs. An array of particle detectors measures a 2 dimensional spatial distribution of particles in the shower and a time distribution of the arrival of the particles in the shower as it intersects the ground plane. The surface detectors are placed far apart from one another, sampling the shower far from its core. The ground array is in fact a sampling calorimeter but with a single detector layer located near the shower maximum X_{max}. In this case the atmosphere is analogous to the absorber of the calorimeter. The determination of the shower energy and the direction of the shower axis, i.e. the energy and direction of the primary cosmic ray, is obtained by simultaneously fitting the measured lateral distribution of EM particles and muons and their arrival times. In addition, the proportion of muons with regard to the EM compound provides information about the identity of the primary cosmic ray.

Charged particles in the shower produce fluorescence light in the range between 300 and 400 nm as they pass through the atmosphere. The amount of light produced at each atmospheric depth is proportional to the shower size, i.e. the number of charged particles. A fluorescence detector which images the sky onto an array of photomultipliers can directly measure the longitudinal development of the shower. The integral of the longitudinal profile is a calorimetric measure of the total shower energy. Fluorescence detector can also measure the position of shower axis and provide information on the identity of the primary particle through the observation of the depth (X_{max}) at which the shower maximum occurs.

3.2. Experimental set-up

The Auger Observatories are designed to work in a hybrid mode, employing fluorescence detectors overlooking ground arrays. During clear moon-less nights ($\approx$ 10% of the time) all registered events will be observed by the fluorescence light and also by particle detectors at ground level. The fluorescence detectors will be similar in design to the Hi-Res Fly's Eye detector [17]. The surface array will be made up of water Čerenkov tanks placed approximately 1.5 km apart, and resembles the array successfully operated by the Haverah Park group for more then 20 years [18]. Fig. 5 shows the reference layout of the P. Auger Southern Observatory.

The Auger Observatory will be installed in the southern and northern hemispheres in order to provide full sky coverage. The southern hemisphere detector is particularly interesting since very few detectors took data in the past in this part of the world from where the direction of the

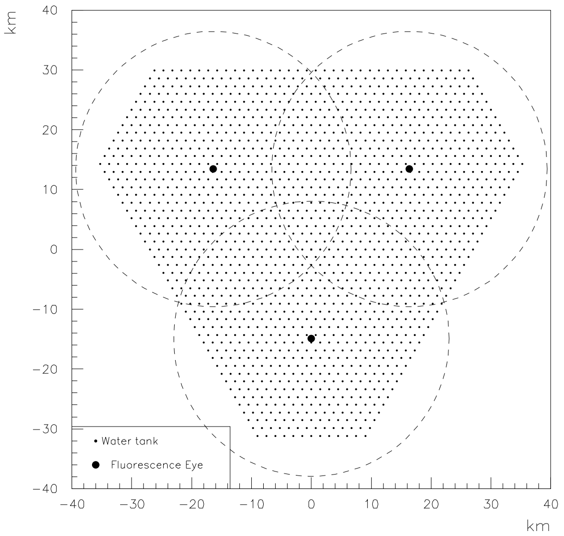

Figure 5. Reference layout for one of the Auger sites

centre of our galaxy is visible. Each site will be equipped with an array of ground detectors covering an area of about 3000 km^2, each of them being overlooked by several fluorescence detectors in order to provide full hybrid detection of incoming high-energy cosmic-rays.

Water Čerenkov Ground Array. The individual stations of the ground array will be water Čerenkov tanks (see Fig. 6) with a round surface of 10 m^2 and a height of 1.2 meters.

Čerenkov radiation emitted by charged particles penetrating the detector will be read out by three photomultipliers. The output signal will be digitised by flash ADCs, with the aim to separate the EM signal (low energy electrons and photons) from the muons crossing the tank. The relative synchronization of the detectors will be provided by the GPS (Global Positioning System) satellites with a precision of a few ns. The communication between the stations and the data transfer to a central computer will be achieved by using radio signals by methods similar to cellular telephone techniques. The stations will be powered by solar panels and batteries which will allow the operation in a stand-alone mode.

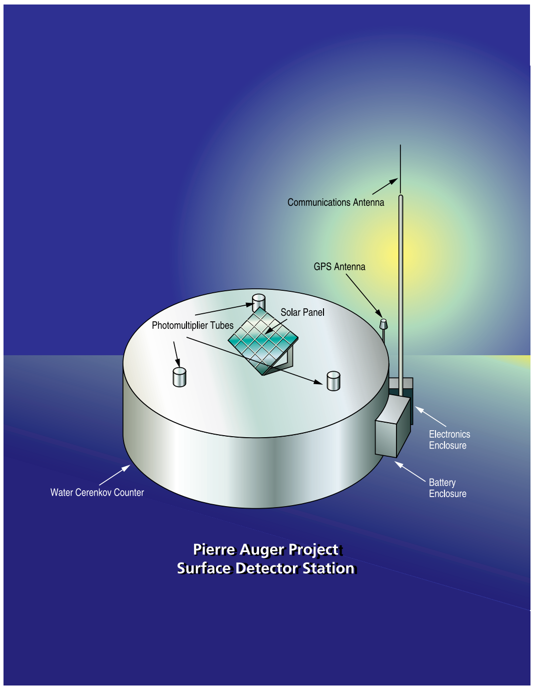

Figure 6. Artist's view of a Čerenkov tank.The drawing shows the phototubes, the solar panel, the GPS and telecom antennae.

Fluorescence detector. The reference design for the fluorescence detector is based on tested Fly's Eye detector [17]. However, there are some minor differences. The pixels are expected to have a 1.5^0 diameter instead of 1.0^0. Each telescope will use 121 pixels instead of 256. With the use of FADC electronics, the pixel size will not impact the longitudinal profile segmentation. The conceptual design of one of the many fluorescence telescopes needed for a 60^0 coverage is seen on Fig. 7. Full description of the P. Auger fluorescence detectors and their simulated performances can be obtained from the Pierre Auger Project Design Report [19].

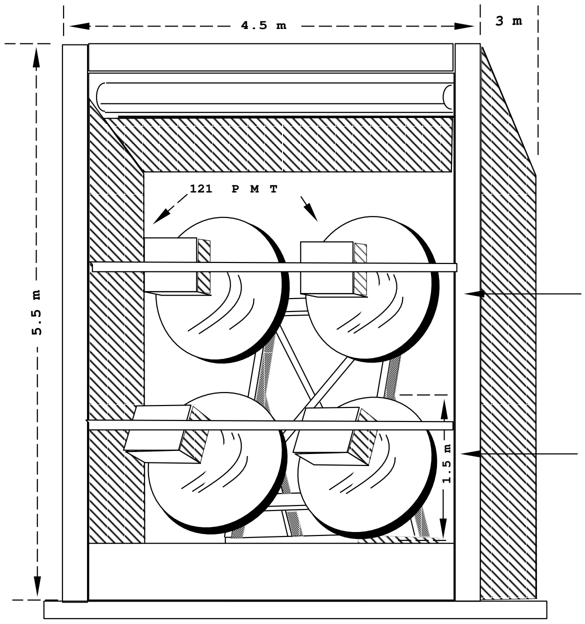

Figure 7. Schematic view of one segment of the fluorescence detector (with its mirrors and PM cameras).

Variations of the above reference design are under study. A promising option is to use Schmidt optics for each telescope. A diaphragm at the mirror's centre of curvature can eliminate the coma aberration that otherwise distorts the spot on the focal surface for off-axis parallel light rays. The elimination of coma enables the field of view to be extended from $15^0 \times 15^0$ to $30^0 \times 30^0$. This would reduce the number of telescopes by a factor of 4.

3.3. Performances

We have carried out extensive simulations to predict the performances of the proposed detector. The simulated air showers data were passed through detailed simulations of ground array and fluorescence detectors to determine the experimental resolutions and acceptance of the detector. Results are summarised in Table 1.

The hybrid data set will yield a subset of events

Table 1
Summary and comparison of reconstruction resolution for the surface array alone and for hybrid data.

	10^{19} eV		10^{20} eV	
	Surface	Hybrid	Surface	Hybrid
$\Delta\Theta$	2.0^0	0.35^0	1.0^0	0.35^0
$\Delta core$	80 m	29 m	40 m	29 m
$\Delta E/E$	18 %	4.3 %	7 %	2.5 %
ΔX_{max}		17 gcm^{-2}		$15gcm^{-2}$

which are particularly well measured, having independent data on energy and direction. Resolutions on this events are significantly improved over that of the surface array alone. When coupled with the determination of X_{max}, these will greatly enhance the analysis of cosmic ray composition.

Aperture of the Auger detector depends on trigger conditions. It has a nice feature that it is constant above an energy level which is determined by the alerted station multiplicity. In case the trigger requires at least five alerted stations a constant aperture of 14000 $km^2 sr$ above $10^{19.1}$ eV is obtained and it falls to only 10 % at $10^{18.3}$ eV. The spectrum measurement can be easily extended to lower energies by simply changing the trigger conditions. Details can be found in P. Auger Project Design Report [19].

4. SUMMARY

The reference design of P. Auger Observatory is now fixed. All the technical issues are still under the process of optimisation and testing. The funding of the Southern Observatory has been approved by the funding agencies in Argentina, France, Germany, Slovenia, UK and USA. Construction of the engineering array of approximately a 100 km^2 on the southern hemisphere site has started and we expect first hybrid data in the year 2001.

P. Auger Observatory will be the only hybrid detector having the capability to distinguish between currently favoured scenarios in astrophysics and cosmology. It may also be the first experiment to open a window to cosmic-ray and neutrino astronomy.

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